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The formation of bars and disks in Markarian starburst galaxies

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Abstract. We have proposed in a companion paper (Considère et al. 2000) that bars appeared recently in massive starburst nucleus galaxies. We now test this hypothesis on an extended sample of barred and unbarred Markarian starburst galaxies, using several samples of normal galaxies as control samples.

In support of this hypothesis, we show that the proportion of barred galaxies is much lower in Markarian starburst galaxies than in normal galaxies. In addition to this deficiency of bars, we find that Markarian starburst galaxies have smaller disks than normal galaxies, and that the disks of unbarred starburst galaxies are smaller, on average, than barred ones. Finally, we show that the Markarian starburst galaxies do not seem to follow the local Tully–Fisher relation.

Various alternatives are examined to explain the deficiency of bars and the small disk dimensions in Markarian starburst galaxies. One possibility, which is in agreement with the young bar hypothesis, is that the formation of disks happens after the formation of bulges and that bars appear only later, when enough gas has been accreted in the disk.

Key words: Galaxies: starburst – Galaxies: spiral – Galaxies: formation

1. Introduction

Since their discovery some thirty years ago, starburst galaxies have been a swiftly growing subject of interest.

This interest is stimulated today by the discovery of many high-redshift star forming galaxies which may have characteristics similar to the nearby starburst galaxies (Steidel et al. 1996, 1999; Lilly et al. 1999). However, the nature of the starburst phenomenon still eludes understanding.

When the massive starburst nucleus galaxies (SBNGs) were discovered, for example, it was generally thought that they were well-evolved galaxies which had been rejuvenated by interactions with nearby companions (Huchra, 1977; Tinsley & Larson, 1979; Kennicutt, 1990). But as many observations have shown, starburst galaxies generally do not reside in high galaxy density regions (Iovino et al., 1998; Coziol et al., 1997a;

Hashimoto et al., 1998; Loveday et al., 1999), which favor interactions, and only a fraction of them (between 25% and 30%) have obvious luminous companions (Telles & Terlevich, 1995; Coziol et al., 1997a).

The assumption that SBNGs are well-evolved galaxies is also challenged by observations. SBNGs generally have abnormal chemical abundances: they are metal-poor compared to normal galaxies with similar morphology and luminosity (Coziol et al., 1997b) and they also present an unusual excess of nitrogen abundance in the nucleus (Coziol et al., 1999).

It appears that SBNGs are engaged in an important phase of formation of their stellar population, but also of their chemical constituents. One simple explanation of these phenomena is that nearby SBNGs are examples of “young” galaxies in their formation process. But is this the only alternative?

One popular assumption is that a bar may be an efficient mechanism by which gas can accumulate in the nucleus of an evolved galaxy to start a burst of star formation. This structure would also produce some of the chemical anomalies encountered in SBNGs. Indeed, it is generally observed that normal barred spiral galaxies have shallower metallicity gradients than unbarred ones (Vila-Costas & Edmunds, 1992; Edmunds & Roy, 1993; Zaritsky et al., 1994; Martin & Roy, 1994). From a theoretical point of view, a bar is expected to funnel unprocessed gas from its outer parts toward its nucleus (Noguchi, 1988), which decreases the metallicity gradient by reducing the metallicity in the nucleus.

We have in fact verified that bars cannot be at the origin of the nuclear bursts in SBNGs (Considère et al. 2000). We searched for the influence of the bar on star formation and chemical evolution in a sample of 16 Markarian galaxies with strong bars and intense star formation. We studied the distribution of ionized gas and the variations of oxygen and N/O abundance gradients along the bar. No relations were found between these different characteristics and the bar properties.

The aim of the present paper is to put the results of our companion paper (Considère et al. 2000) in a broader context. Using a large sample of galaxies, we test our interpretation that bars in SBNGs appeared only relatively recently. We show that this hypothesis is consistent with a scenario where these galaxies are “young” galaxies still in formation.

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2. The frequency of bars in Markarian starburst galaxies

How can we further test whether bars in SBNGs are indeed young? In Considère et al. (2000), we showed that the bursts in the nuclei of SBNGs have not been triggered by young bars, but by some event which probably took place a few Gyrs in the past. In general, therefore, the bursts in the nuclei of these galaxies must be older than the bars. We can use this assumed age difference to verify our hypothesis. In a complete sample of SBNGs, one should expect the frequency of barred galaxies to be proportional to the typical age of bars divided by the typical age of nuclear bursts. Therefore, if bars are young as compared to the nuclear bursts, their frequency in the sample will be low.

To perform this test, we have gathered information from the literature on all Markarian galaxies (1500 galaxies), compiled by Mazzarella & Balzano (1986). Using LEDA, we have extracted 512 galaxies which had a morphological type, were classified as starburst and were more luminous than magnitude $M_B = -18$. We adopted this magnitude limit in order to select only SBNGs, and not HII galaxies. It is also known that the completeness of the Markarian sample decreases for galaxy magnitudes $M_B \geq -18$ (Coziol et al. 1997a). The present sub-sample represents one-third of the whole sample of Markarian galaxies. Although it cannot be considered statistically complete, it forms the largest sub-sample of massive starburst galaxies on which to apply our test¹.

The distribution of the morphologies of the Markarian starburst galaxies is presented in Fig. 1. We find that only 109 Markarian starburst galaxies (21%) are barred. This frequency must be compared to the frequency of bars in normal galaxies: just over half of all normal galaxies are considered barred (de Vaucouleurs, 1963; Sellwood & Wilkinson, 1993).

The above statistics may obviously be biased, if many unseen bars are present in the sample, as bars are often difficult to detect in the optical (see for example Eskridge et al. 1999). However, such a large discrepancy between normal and Markarian starburst galaxies cannot be attributed to observational biases only. Even if we assume that many more Markarian starburst galaxies are barred, we would need a proportion of barred galaxies significantly larger than 50% (the standard proportion in normal galaxies) to confirm that bars play an important role in the starburst phenomenon.

If the Markarian starburst sample were complete, the fraction of bars would indicate exactly how old bars are in comparison to the nuclear bursts. But, because of incompleteness, the above frequency can only give a qualitative estimate of the age difference. In Considère et al. (2000) we estimated that the nuclear bursts could be a few 10^9 yrs old, while bars may be only a few 10^7 yrs old, which leads to an estimated frequency of barred galaxies of 1%. This is lower than observed by only a factor 10. Taken at face value, this means that the bursts may be younger – or the bars older – than estimated by a factor 10. These two possibilities (or any solution in between) are consistent with our observations. Taking into account the crudeness

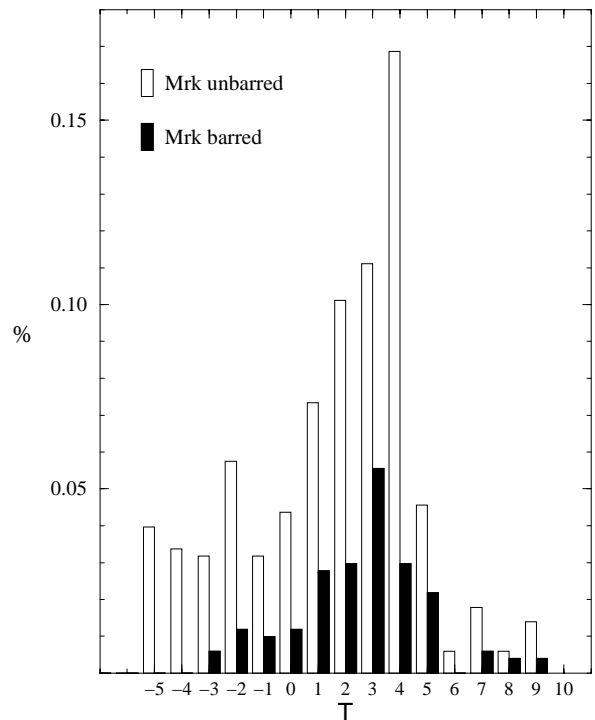


Fig. 1. Distribution of morphologies in a sample of 512 Markarian galaxies classified as starbursts. This sample represents one-third of the Markarian catalogue. The histogram shows the percentage of the total population in each morphological class. We also distinguish between barred and unbarred galaxies

of our age estimates and the conditions of the test, this result is reasonable.

From the above analysis, we conclude that these statistics support the conclusions of Considère et al. (2000), that bars are not at the origin of the nuclear bursts in SBNGs, because they are too young and appeared only recently in these galaxies.

3. The formation of the disk in Markarian starburst galaxies

The next step is to relate the recent appearance of bars in SBNGs to the starburst phenomenon. In earlier papers, we showed that SBNGs are probably the remnants of mergers of gas-rich and small-mass galaxies, a process which we identified with hierarchical formation (Coziol et al. 1997b; 1998). We also found an interesting difference between the chemical abundance of early- and late-type starburst galaxies suggesting that their chemical evolution followed slightly different paths, namely that late-type starburst galaxies accreted more gas than stars during their formation (Coziol et al., 1998). This suggests an alternative scenario for the disk formation in late-type starburst galaxies.

The merging of gas-rich and small-mass galaxies – main origin of the bursts – produced the bulk of stars and chemical elements. Depending on the density of the environment,

¹ We remind the reader that the starburst galaxies studied by Considère et al. are all Markarian galaxies.

Table 1. Comparison of Markarian starburst and normal spiral galaxy properties

Sample	# gal.	$\langle M_B \rangle$	$\langle \mu_B \rangle$ (mag arcsec $^{-2}$)	$\langle Dist. \rangle$ (Mpc)	$\langle R_{25} \rangle$ (kpc)	$med(R_{25})$ (kpc)	$med(R_{25})$ (Sab/Sb) (kpc)
Normal unbarred	437	-20.7 ± 5.4	23.5 ± 0.5	55 ± 25	31 ± 13	26.9	30.6
Normal barred	598	-20.2 ± 1.0	23.5 ± 0.5	44 ± 23	29 ± 12	26.1	32.7
Mark unbarred	393	-20.5 ± 0.8	22.8 ± 0.8	92 ± 25	20 ± 10	17.7	19.0
Mark barred	109	-20.4 ± 1.0	23.0 ± 0.6	67 ± 23	23 ± 12	22.0	24.5

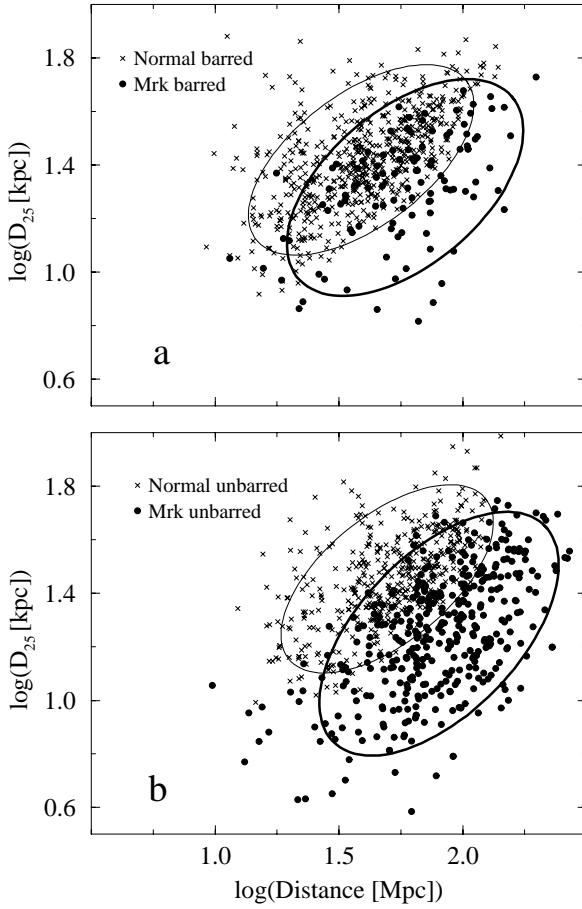


Fig. 2. Disk radius R_{25} , as a function of galaxy distance. **a** : the sample of normal barred spiral galaxies of Mathewson & Ford (1996) is compared to the Markarian barred starburst galaxies. **b** : the unbarred normal and Markarian spiral galaxies are compared. The 2σ dispersion ellipses are shown. The thin ones encircle the normal galaxies and the thick ones the Markarian starburst galaxies. In general, the Markarian starburst galaxies have smaller disks than normal galaxies

this first phase of formation produced galaxies with different bulge/disk ratios, with a bias towards higher ratios, because mergers favor the formation of early-type galaxies. But because the galaxy spatial density where these galaxies formed is relatively low (starburst is a field phenomenon), an important

fraction of the gas did not collapse and subsisted in a temporary reservoir around the galaxies. As time passed, the reservoir emptied as the gas fell on the galaxies, forming or increasing their disks. When the disk had accreted enough gas a bar appeared.

The validity of the above scenario can be checked in the following way. If starburst galaxies are still in the process of formation, they should have smaller disks than normal galaxies. Moreover, barred starburst galaxies should have larger disks on average than unbarred ones. To test these predictions, we compare the isophotal disk radii (R_{25}) of Markarian barred and unbarred starburst galaxies with those of normal galaxies. The result is shown in Fig. 2, where the disk sizes are presented as a function of distance. The normal barred and unbarred spiral galaxies are represented by the sample of Mathewson & Ford (1996). The disk radii were all extracted from LEDA (Paturel et al., 1997). The mean radii are presented in Table 1. Unbarred starburst galaxies do seem to have a smaller disk on average than barred ones. Moreover, starburst galaxies generally have smaller disks than normal (barred and unbarred) spiral galaxies.

It is important to understand the various biases which affect the two samples of galaxies. Because of the Malmquist bias, the normal galaxy sample is biased towards brighter (and thus larger) galaxies as the distance increases. This bias artificially raises the mean dimension of these galaxies. But the Markarian sample is affected by the same bias; even more so, because the sample goes slightly deeper in redshift (see Table 1). The difference between normal spiral galaxies and Markarian starburst galaxies, therefore, cannot be explained by such a bias. Moreover, the difference observed between the disk radii of barred and unbarred Markarian starburst galaxies cannot be attributed to the Malmquist bias, since unbarred starburst galaxies are on average located further away than barred ones (see Table 1).

The above statistics may still be affected by another bias, because the size of galaxies depends on their morphological type. Roberts & Haynes (1994) have shown that the median isophotal radius for a sample of 7930 galaxies in the UGC catalogue varies with morphology. The radius is maximum for intermediate types Sab/Sb and falls for earlier and later types. How does this affect our result?

In Fig. 3, we present the isophotal radius of the Markarian starburst galaxies as a function of morphology. As a comparison sample, we could not use that of Roberts & Haynes and used Mathewson & Ford's sample of normal spiral galaxies

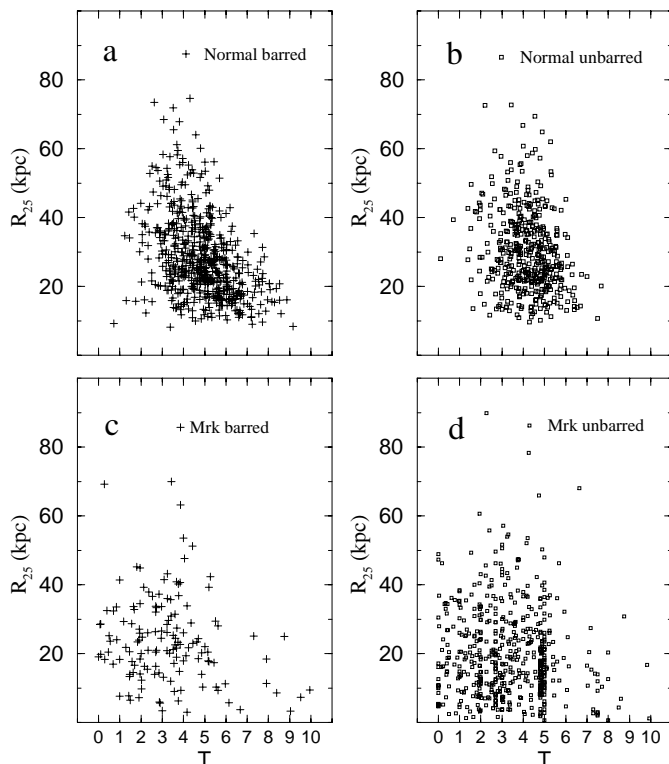


Fig. 3. Disk radius R_{25} , as a function of galaxy morphology. **a** and **b**, the normal barred and unbarred spiral galaxies of Mathewson & Ford (1996). **c** and **d**, the Markarian barred and unbarred starburst galaxies. The small dimension of the Markarian galaxies is independent of morphology

instead. One can see that the size of the Markarian galaxies does not depend on morphology. The barred and unbarred normal galaxies share the same distribution in morphology, concentrated around types Sb/Sbc. The Markarian galaxies, on the other hand, are more numerous in the types Sab/Sb. We thus have to be careful when comparing the different samples.

The incompleteness of Robert & Haynes' sample is well identified: the sample is deficient in low-surface brightness galaxies and high surface brightness compact galaxies. These two deficiencies certainly do not affect the comparison with our sample of Markarian galaxies, which are neither compact nor of low surface brightness.

In their analysis, Robert & Haynes used the median radius because their distributions are not gaussian. The median radius of their sample for Sab/Sb types is 25.1 kpc. This has to be compared with the medians observed in the samples of Markarian and Mathewson & Ford (last column in Table 1). The medians for all the morphological types is also given in Table 1. The spiral galaxies in the sample of Mathewson & Ford have slightly higher median values than Roberts & Haynes' sample. This is probably because of the Malmquist bias. While the Markarian barred galaxies are comparable in size to galaxies in the sample of Robert & Haynes, unbarred ones are significantly smaller.

4. The effect of small disks on the Tully–Fisher relation

Do the small disks of Markarian starburst galaxies affect their kinematics? In normal spiral galaxies, the maximum rotation velocity is correlated to the absolute magnitude by the Tully–Fisher (TF) relation. According to this relation, massive galaxies have to rotate more rapidly than small-mass galaxies in order to sustain their mass. Table 1 shows that the Markarian galaxies have luminosities and surface brightnesses which are comparable to those of normal galaxies. We thus expect them to be slow rotators if they follow the TF relation, assuming that they have a normal mass-luminosity ratio (\mathcal{M}/L).

We have determined the TF relation for the Markarian starburst galaxies, using the maximum rotation velocities found in LEDA. In Fig. 4, the starburst galaxies are compared to the normal barred and unbarred spirals from Mathewson & Ford (1996). Using the latter sample, Simard & Pritchett (1998) determined the local TF relation (the continuous line in Fig. 4). The use of rotation velocities found in LEDA gives a slightly lower value than the one found by Simard & Pritchett for the local TF relation, as the observed points tend to fall slightly below the line.

We find that the Markarian starburst galaxies are not slow rotators. They have rotation velocities comparable to those of massive normal galaxies. Then how do these galaxies readjust their structure to follow the local TF relation? In a galaxy in dynamical equilibrium, the mass \mathcal{M} is proportional to $V_{max}^2 R$, where R is the radius of the disk and V_{max} is the maximum rotational velocity. On the other hand, the total luminosity L is proportional to $\Sigma_0 R^2$, where Σ_0 is the central surface brightness. Combining the two, we obtain :

$$R \Sigma_0 (\mathcal{M}/L) \propto V_{max}^2 \quad (1)$$

In other words, a smaller galaxy must either have a higher surface brightness or a higher (\mathcal{M}/L) to fall in the same region of the TF relation as normal galaxies. Since the Markarian starburst galaxies have normal surface brightnesses (see Table 1), they should have a higher (\mathcal{M}/L). But this conclusion goes contrary to what is usually admitted for starburst galaxies, where the presence of massive stars raises the luminosity at the expense of the mass.

What appears as a contradiction might perhaps not be one, if one looks more closely at Fig. 4. The Markarian starburst galaxies in fact do not follow any linear relation, although their rotational velocities are consistent with values predicted by the local TF relation. A linear regression applied to the unbarred Markarian galaxies yields a coefficient of correlation of only 43%. The correlation is slightly better for barred starburst galaxies with 53%. The dispersion of the data is indeed significantly higher in the Markarian sample than in the normal one. This higher dispersion is not caused by spurious data; we have eliminated Markarian galaxies with large uncertainties in V_{max} (> 10 km/s) in Fig. 4. Therefore, this is an intrinsic characteristic of the sample: the Markarian galaxies do not seem to follow the local TF relation.

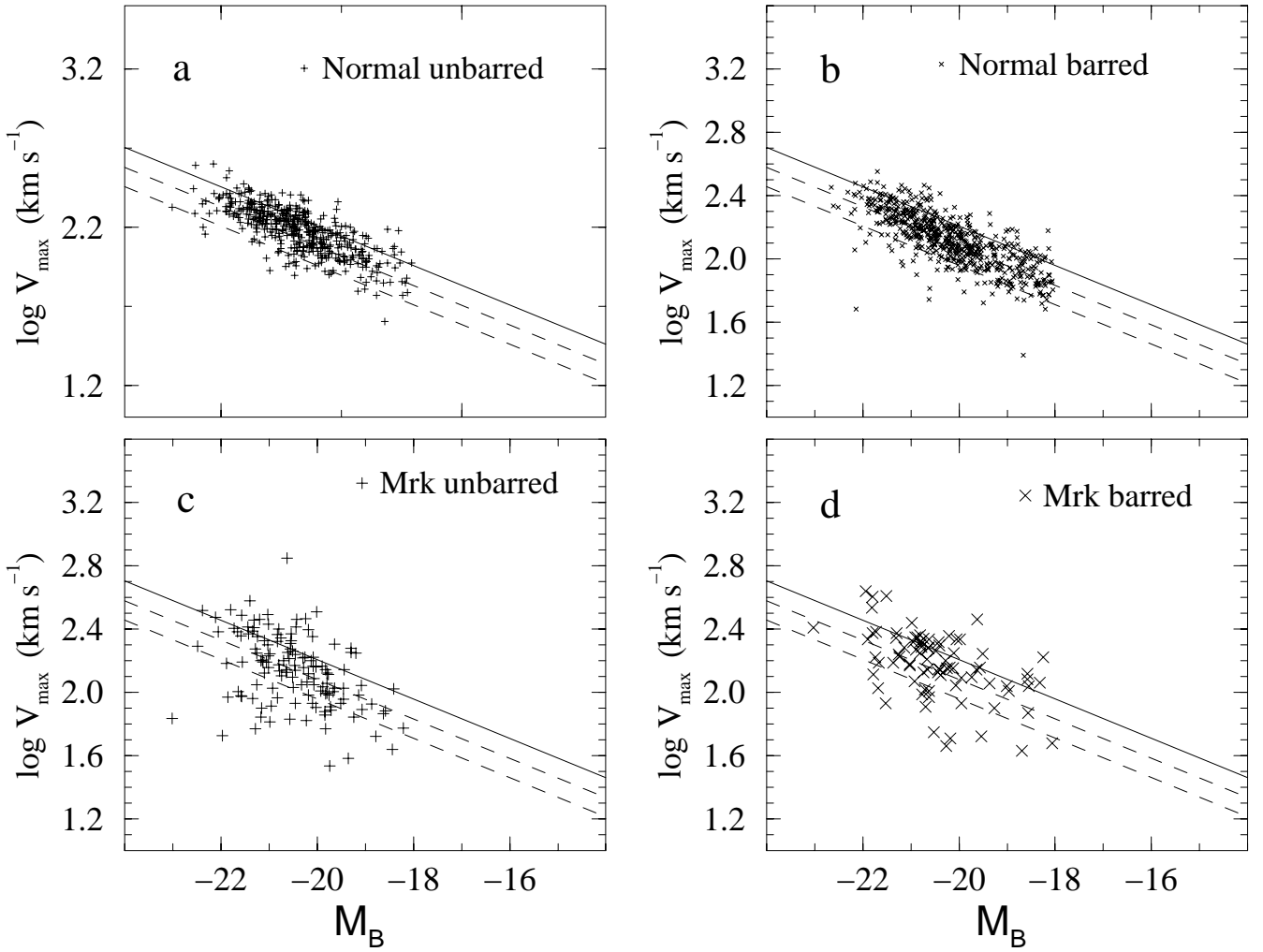


Fig. 4. Tully–Fisher relation for (a) normal unbarred and (b) barred spiral galaxies; (c) Markarian unbarred and (d) Markarian barred starburst galaxies. The continuous line is the local Tully–Fisher relation determined by Simard & Pritchett (1998). The dashed lines represent the same relation shifted by $\Delta M_B = 1.0$ mag and 2.0 mag

Although the origin of the TF relation is still ill-understood, it is generally believed that this relation is fundamental and that it must have arisen at the formation of galaxies (Burstein & Sarazin, 1983; van den Bosch, 1999; Steinmetz & Navarro, 1999; Syer et al., 1999). The present observation is consistent with this assumption, since we believe SBNGs are still in their formation phase. It implies that the disks in these galaxies are not in a state of dynamical equilibrium.

5. Alternatives to the disk formation scenario

Are there other ways to explain the paucity of barred galaxies in the Markarian sample and their small disk dimensions? A majority of Markarian galaxies might not have a bar because the conditions required for the occurrence of a burst do not allow it. It is considered, for instance, that interactions can destroy the bar. But in Considère et al. (2000) we have found three clear cases of interacting galaxies where the bars seem as strong as, if not stronger than other bars in the galaxy sample. Further-

more, this hypothesis does not explain the small dimensions of the disks.

The fewer bars and the smaller disks in starburst galaxies could be due to higher dust extinction. A high level of obscuration is effectively observed in some ultraluminous infrared starburst galaxies (Mirabel et al., 1998). However, these objects are more an exception than the rule in the nearby Universe. High extinction does not generally apply to starburst galaxies (Buat & Burgarella, 1998). Moreover, in this case the occurrence of smaller disks would imply that the dust opacity becomes higher in the outer disk, while the contrary is usually found: spiral galaxies are optically thin in the outer regions and moderately opaque at their center (Giovannelli et al., 1994; Moriondo et al., 1998; Xilouris et al., 1999).

There is also clear evidence that the outer regions of disks are relatively unevolved at the present epoch (Ferguson et al., 1998), which is consistent with the idea that disks are younger than bulges, as proposed in our scenario.

As a last alternative, it may be that, at the end of their evolution, the Markarian galaxies will produce mostly small disks and unbarred galaxies. A similar hypothesis was recently suggested to explain the appearance of a large number of relatively small galaxies with high luminosities at high redshifts (Lilly et al., 1998). If what we observe in nearby starburst galaxies is of the same nature, then this means that at each epoch we always see some intense star forming activity which concerns only galaxies of small dimensions. This is an intriguing hypothesis which would imply that Markarian galaxies are of a peculiar nature.

None of the above scenarios predicts that Markarian starburst galaxies should not follow the local TF relation. The dispersion observed in Fig. 4 for the Markarian starburst galaxies cannot be explained assuming only higher dust extinction. This hypothesis might work for galaxies which are above the local TF relation in Fig. 4, but not for galaxies which are below; they would need to be more luminous than normal. It is also hard to understand why dust extinction changes neither the distribution of luminosity nor the surface brightness of these galaxies (see Table 1). We need a very contrived model for dust distribution in order to explain all these observations.

In their paper on star forming galaxies at high redshifts, Simard & Pritchett (1998) found that these galaxies do not follow the local TF relation. They concluded that this could be explained by assuming that high redshift star forming galaxies are more luminous, by an average of one or two magnitudes, than normal nearby galaxies. But there is no evidence that the B luminosity of the local Markarian starburst galaxies, and of SBNGs in general, differs significantly from that of normal galaxies (see Table 1 and Coziol 1996). Furthermore, Simard & Pritchett do not know if the disks of their galaxies are smaller than those of normal galaxies, as in nearby starburst galaxies. If the Markarian starburst galaxies do not follow the local TF relation because they are more luminous than normal spiral galaxies, then, taking into account their small dimension, nearby starburst galaxies must be much more luminous than “comparable” star forming galaxies at high redshifts. This argument suggests that the reason why Markarian galaxies do not follow the local TF relation is that they are still in the process of forming their disks. This may be true also for forming galaxies at high redshifts.

6. Conclusion

Of all the alternatives presented above, none is simpler than our scenario for the formation of the nearby SBNGs. It has many advantages: it explains the origin of the bursts in these galaxies (the galaxies are in a burst phase because they are still forming), and it fits their star formation history (Coziol, 1996), their chemical evolution (Coziol et al. 1998; 1999) and the properties of their bars (Considère et al. 2000).

According to this scenario, bulges of galaxies form first and the disks form later mostly through gas accretion. It predicts that young galaxies initially look like unbarred early-type spirals with small disks. Then, as the disk grows, they change

into late-type and giant barred spiral galaxies (Kauffmann et al., 1993; Baugh et al., 1996; Andredakis, 1998). This transformation may explain why Markarian starburst galaxies are so frequent among Sa and Sb galaxies (see Fig. 1). The fact that we do not see many Sc galaxies in the sample of Markarian starburst galaxies suggests that these galaxies form differently (Andredakis, 1998).

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